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Effects of workpiece preheating on surface roughness, chatter and tool performance during end milling of hardened steel D2

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ABSTRACT

This paper presents the results of experimental investigations conducted on a vertical machining centre (VMC) to ascertain the effectiveness of brazed circular polycrystalline cubic boron nitride (PCBN) inserts in end milling of hardened steel AISI D2 (60–62 HRC), under room temperature and workpiece preheated conditions. Comparison was made in terms of intensity of chatter, chip formation instability, tool wear and metal removal capacity of the tool and surface roughness of the machine parts. It has been found that chips formed are composed of primary and secondary serrated teeth and their formative frequencies have definite relationship with the chatter frequencies. Though initial average flank wear of the tool during preheated machining is found to be slightly higher compared to that of room temperature machining, the extrapolated tool life appears to be higher in the case of preheating. The main mechanisms of tool failure are found to be superficial plastic deformation, diffusion and notching. It has been observed that feed per tooth, cutting speed, preheating and amplitude of chatter have direct bearing on the surface roughness. It has been observed that preheated machining of the material leads to surface roughness values well below 0.4 μm, such that the operations of grinding as well as polishing can be avoided at the higher cutting speeds.

1. Introduction

The benefits for the manufacture of components from hardened steel are substantial in terms of reduced machining costs and lead times compared to the more traditional machining route (Koshy et al., 2002). AISI D tool steel group is extensively used in making moulds and dies, but the machinability of this group is very poor. Boehner et al. (1999a,b) found that TiAlN coated carbide tools were suitable in high speed milling of AISI D2 tool steel having hardness of 62 HRC. Dolinsek et al. (2004) found close relationship between chip formation frequency and chip shape. Hosokawa et al. (2005) found that cutting temperature was by 50 °C lower in case of the CBN tool compared to coated tools because of its high thermal conductivity. Boehner et al. (1999a,b) observed that when machining hardened steel D2, the cutting temperatures is significantly higher than what was observed in machining hardened H13, which largely accounts for the poor tool life in machining D2. It was established by Amin and Abdelgadir (2003) that preheating had great potential in lowering chatter. The primary objective of preheating is to enhance the ductility of the material for easier chip formation and better chip flow over the rake surface of the

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tool. However, to avoid softening of the hardened workpiece low preheating temperature (100–150 °C) could be applied. Hence it was aimed at investigating the influence of low temperature workpiece preheating on chatter and various parameters of machinability of hardened steel AISI D2 in end milling using circular coated tungsten carbide and PCBN inserts.

2. Methodology and experimental setup

Workpiece (AISI D2) hardness was 60–62 HRC. End milling operation was conducted using a 32 diameter tool fitted with two circular inserts. Cutting speeds used in the experiments were, V_c = 50, 75, 100, 125 and 150 m/min, values of feed rate were, f_z = 0.05, 0.1 mm/tooth, value of axial depth of cut, d_c = 1 mm. Full immersion cutting was employed. Cutting tests were conducted on vertical machining center of model 'PMC-10T24'. Vibration signals were recorded using a 16-channel Dewetron data acquisition system. Analysis of the recorded and the stored signals were done using DASYLab software version 5.5. The same experimental setup used by Amin (1983) for the preheated machining and vibration monitoring was used. Induction heating machine of 25 kV A capacity was used for preheating (online heating) of the workpiece. Different current values were used under the varying feed rates to achieve the preheating temperature from 50 to 150 °C.

3. Results and discussion

3.1. Free vibration analysis

Free vibration analysis of the VMC system was first conducted to determine the natural frequency of the system components. Following are the excited frequencies (Hz) with their node numbers: 582.83 (1), 1165.66 (2), 1768.09 (3), 2346.94 (4), 2925.79 (5), 3492 (6), 4117.9 (7) and 4700.73 (8). Two main natural frequency peaks at 2347 and 4118 Hz were found to belong to the tool and the spindle, respectively. All the peaks are found at spacing of approximately the frequency of the lowest excited peak (583 Hz), which is termed as node 1 and the remaining peaks are given numbers in ascending order. It is expected that during machining excitation of vibration could occur at any one of these frequencies, since vibrations are caused due to resonance, when the chip serration frequency coincides with any one of the natural frequencies of the system (Amin, 1983).

3.2. Analysis of vibration/chatter during machining

Vibration signals captured during machining were carefully analyzed and the peak amplitudes and their corresponding frequencies were recorded. Sample of FFT plot for preheated machining at the cutting speed of 150 m/min with feed rate of 0.1 mm/tooth is shown in Fig. 1. The lower and the higher chatter (excited) frequencies are shown as a function of cutting speed in Fig. 4a and the peak acceleration amplitude values at the lower and higher frequencies are plotted against cutting speed in Fig. 2. It was evident from Figs. 1 and 4a that there were two major peaks during actual machining, one at approximately 1250 Hz, close to the second node and the other at 6000 Hz, close to the 11th node during room temperature machining.

During preheating the lower excited frequency is 1300 Hz, which is close to the secondary chip serration frequency and the higher frequency is 6000 Hz is close to the primary chip serration frequency. These two frequencies are also close to the 2nd and the 11th nodes respectively. It was also observed that at 50 m/min the lower frequency peak (at 1300 Hz) had almost vanished due to preheating, though the higher frequency peak is higher in the latter case due to the closeness of the natural frequency node and the primary chip serration frequency. At 150 m/min the acceleration amplitudes at both the excited frequencies are very small compared to those at 50 m/min (Figs. 1 and 2) (approximately 100 times) during both preheated and room temperature machining. This is because of no matching between the primary and secondary chip serration frequency and the excited frequencies; with the chip frequencies much higher than the natural frequencies. It was observed from Fig. 4a that the lower chatter frequencies remain practically constant over the entire cutting speed range except at the speed of 125 m/min, which may be related to the sharp rise in the chip serration frequency. The higher chatter frequency also remains constant at all speeds except at 125 m/min, where the frequency jumps to higher node.

Comparing the effect of feed rate from these two figures, it is observed that the acceleration peaks are much higher at the higher feed rate of 0.1 mm/tooth compared to those at 0.05 mm/tooth for both frequencies. Comparing the effect of cutting speed on peak amplitude it is observed

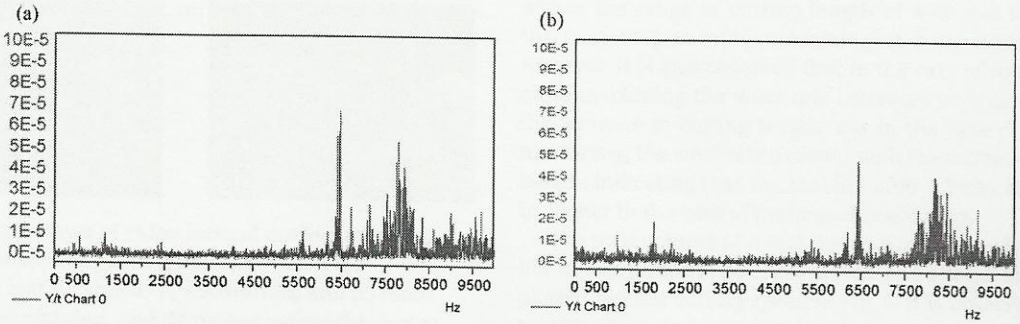

Fig. 1 – Acceleration amplitudes during: (a) room temperature machining and (b) preheated machining (current, I = 351 A, V = 150 m/min, f = 0.1 mm/tooth, DOC = 1 mm).

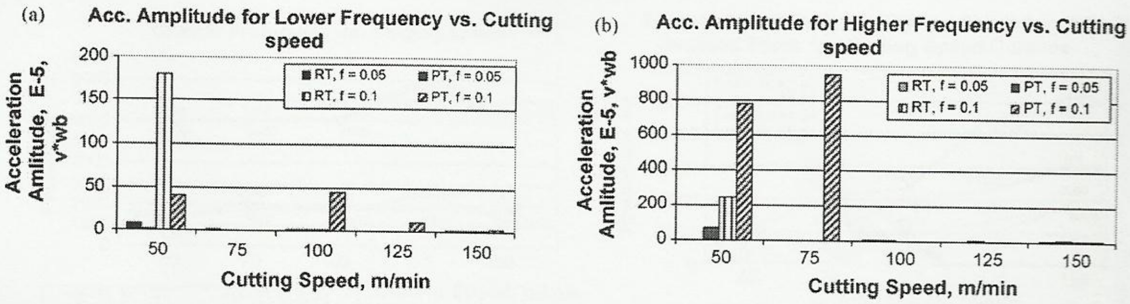

Fig. 2 – Comparison of the peak acceleration amplitudes during room and preheated machining at feed rates 0.05 and 0.1 mm/tooth and DOC 1 mm for: (a) lower chatter frequency and (b) higher chatter frequency.

that the lower frequency chatter is the most intensive at the cutting speed of 50 m/min in the case of room temperature machining and preheating leads to lowering of the maximum acceleration amplitude by almost 4.5 times. With respect to the chatter at higher frequency, cutting speeds 50 and 75 m/min are more venerable to vibrations. It is also observed that preheating results in higher acceleration amplitudes of the higher frequency modes. At the higher speeds the amplitude peaks die down causing no serious threat of chatter. This happens because the system goes out of resonance whence the chip serration frequency is much higher compared to the excited natural frequency of the system components.

3.3. *Chip analysis*

Chips, formed during the two machining methods with the feed rate of 0.1 mm/tooth, were analyzed (Fig. 3a–d). From the figure it is observed that the chips formed at 50 m/min during machining under room temperature condition have very clear secondary serrated teeth formed at the free edge. This is related to higher amplitude of chatter at 50 m/min. But chips formed at 150 m/min have less pronounced secondary serrated teeth at the free edge. This also indicates the absence of chatter at this speed. Serrated teeth are also formed at the free edge of the chip during machining under preheated condition.

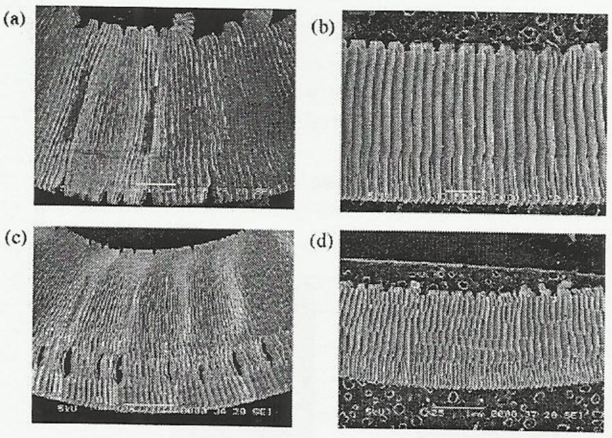

Fig. 3 – SEM top views of chips formed during: (a) room temperature machining and (b) during preheated machining at cutting speed, $V_c = 50$ m/min; and (c) room temperature machining, and (b) preheated machining at cutting speed, $V_c = 150$ m/min. Feed rate, $F_z = 0.1$ mm/tooth, DOC = 1 mm. Magnification: 40×.

Primary serrated teeth are also observed under both the cutting conditions. The teeth formed are more pronounced in the case of preheated machining. The frequencies of the primary and the secondary serrated teeth are calculated from the SEM micrographs taking into consideration of the coefficient of chip shrinkage, cutting speed and magnification of the picture. It is observed from Fig. 4 that the primary chip serration frequency is higher at room temperature machining.

It is also observed from (Fig. 4a and b) that the secondary chip serration frequency is very close to the lower chatter frequency for room temperature machining at 50 m/min. For preheated machining the secondary chip serration frequency at 50 m/min is approximately 2 times the lower chatter frequency. The higher chatter frequency also is found to maintain a relationship with the secondary chip serration frequency (Fig. 4a and b). During preheated machining the chatter frequency is found to be close to integer values of the secondary or the primary chip serration frequency at the investigated cutting speeds.

3.4. *Tool wear analysis*

The average flank wear, VB vs. linear cutting length plots for two cutting speeds 125 and 150 m/min are shown in Fig. 5. Average flank wear at 150 m/min is only slightly higher than that of 125 m/min. Secondly the total average flank wear within the range of cutting length of 4000 mm is higher in the case of preheated machining at both cutting speeds. However, it is also observed that in the case of room temperature machining the wear rate increases exponentially with the increase in cutting length, but in the case of preheated machining, the wear rate declines with the increase in cutting length, indicating that the tool life after 0.3 mm of VB would be higher in the case of preheated machining.

The total volume of metal that can be removed during tool life in every case is also calculated and shown as bar chart plotted against cutting speed in Fig. 6. It is observed that the tool life and volume of metal that can be removed per tool life is higher in the case of preheated machining assuming the standard value of VB of 0.3 mm.

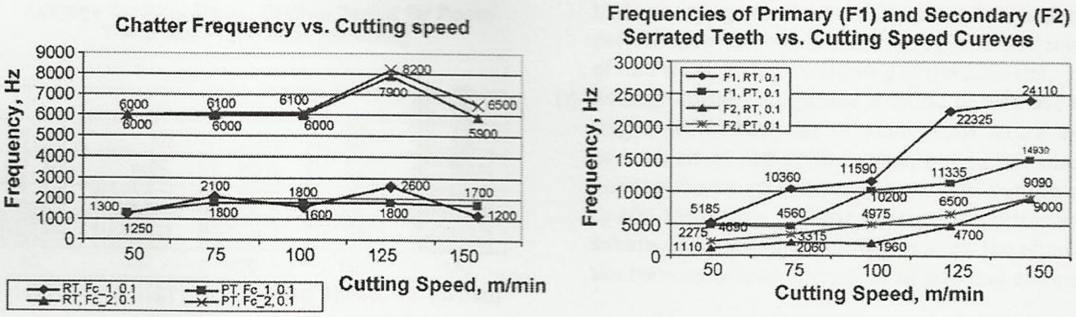

Fig. 4 – (a) Low and high chatter frequencies vs. cutting speed curves and (b) primary chip serration frequency, F1 and secondary chip serration frequency, F2 vs. cutting speed curves.

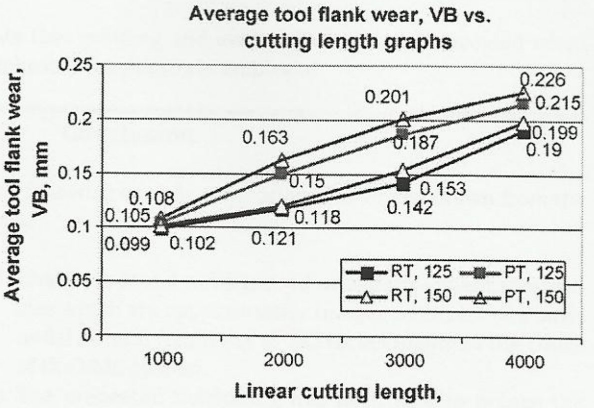

Fig. 5 – Average flank wear, VB vs. linear cutting at 125 and 150 m/min.

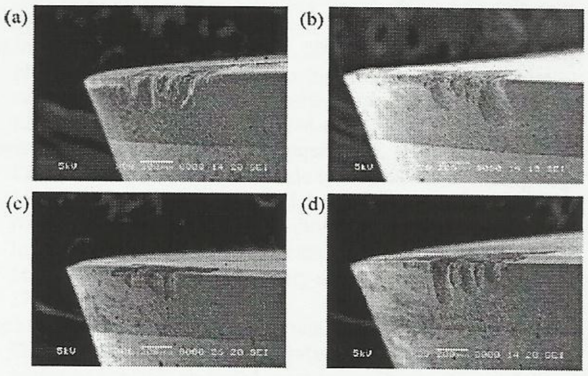

Fig. 7 – SEM photographs of the worn tools at the end of machining tests: (a and b) at 125 m/min, (c and d) at 150 m/min, (a and c) under room temperature conditions and (b and d) under preheated conditions. $F_z = 0.1$ mm/tooth, DOC = 1 mm. Initial magnification 80×.

3.4.1. *Analysis tool wear using SEM*

SEM views of the worn tools are shown in Fig. 7a–d. From the SEM photograph the following observations can be made in terms of wear mechanism:

(i) Wear is concentrated at a distance from the nose radius and has the shape of grooves running perpendicular to the cutting edge appearing to be mainly due to notch wear and superficial plastic deformation.
(ii) Worn land appears to be more severely deformed in the case of room temperature machining compared to that under preheated machining.
(iii) Average wear at the nose section is found to be lower in the case of preheated machining. This may be one of the factors for lower surface roughness during preheated machining, particularly at these two cutting speeds.

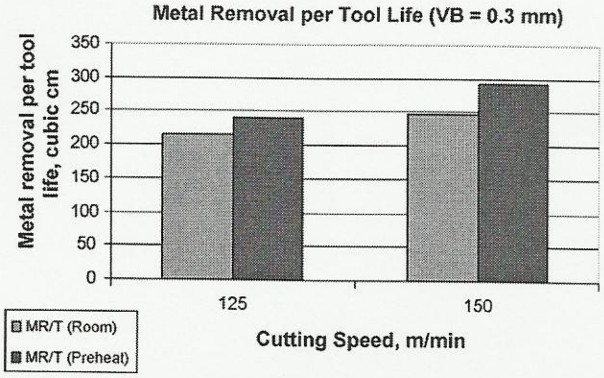

Fig. 6 – Metal removal per tool life allowed at the two cutting speeds. $F_z = 0.1$ mm/tooth and DOC = 1 mm.

3.5. *Comparison of surface roughness produced at various cutting conditions*

Average surface roughness, R_a values are found to increase with cutting speed in the case of room temperature machining, but in the case of preheating the roughness values decrease with cutting speed up to 100–125 m/min (Fig. 8). The values are higher at the two lower cutting speeds for preheated machining for both feed values, but at the higher cutting speeds roughness values are lower for preheated machining for both feed values, especially at the last two speeds, which may be related to higher temperatures generated in the flow zone during preheated machining as it facilitates easier chip flow and material flow relative to the tool surfaces. The absolute values of average surface roughness at the last two speeds are close to or below 0.3 μm, (i.e. below 0.4 μm), which indi-

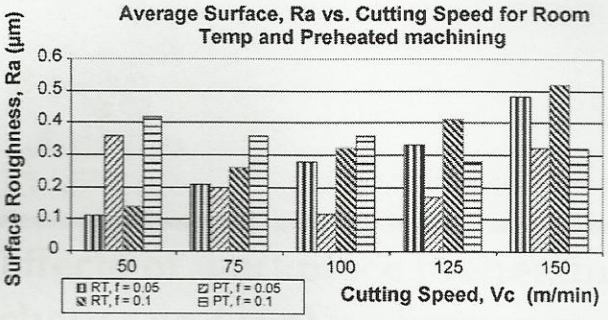

Fig. 8 – Average surface roughness vs. cutting speed plot for room temperature and preheated machining for two feed values: 0.05 and 0.1 mm/tooth.

cate that grinding and even polishing can be avoided when preheated machining is employed.

4. Conclusion

The following specific conclusions have been drawn from the work:

(i) Chatter is found to be caused at two prominent frequencies which are approximately integer multiples of a basic nodal natural frequency of 583 Hz belonging to the chuck of the VMC system.
(ii) The preheated machining has been able to reduce the amplitude of the lower frequency mode of chatter by almost 4.5 times at the cutting speed of 50 m/min, at which chatter is most prominent, with slightly higher amplitude at the higher frequency mode.
(iii) Prominent secondary serrated at the free edge of the chip comprising certain number of primary serrated teeth are observed during room temperature machining. Their frequencies are found to be either equal or approximately integer multiples of the lower chatter frequency.
(iv) Preheating has led to lower average nose wear which facilitated lower surface roughness, especially at the three higher cutting speeds. Notch wear and superficial plastic deformation are found to be a very prominent mechanism of tool wear during machining of the material.
(v) Average surface roughness is found to increase with cutting speed in the case of room temperature machining as a result of higher tool wear, but in the case of preheating the roughness decreases with cutting speed up to 100–125 m/min and the average roughness values are substantially lower, which would allow the elimination of the two costly final operations of grinding and polishing.

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